



Leaching of Cadmium, Tellurium and Copper from Cadmium Telluride Photovoltaic Modules

Progress Report

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ABSTRACT

Separating the metals from the glass is the first step in recycling end-of-life cadmium telluride photovoltaic modules and manufacturing scrap. We accomplished this by leaching the metals in solutions of various concentrations of acids and hydrogen peroxide. A relatively dilute solution of sulfuric acid and hydrogen peroxide was found to be most effective for leaching cadmium and tellurium from broken pieces of CdTe PV modules. A solution comprising 5 mL of hydrogen peroxide per kg of PV scrap in 1 M sulfuric acid, gave better results than the 12 mL H₂O₂/kg, 3.2 M H₂SO₄ solution currently used in the industry. Our study also showed that this dilute solution is more effective than hydrochloric-acid solutions and it can be reused after adding a small amount of hydrogen peroxide. These findings, when implemented in large-scale operation, would result in significant savings due to reductions in volume of the concentrated leaching agents (H₂SO₄ and H₂O₂) and of the alkaline reagents required to neutralize the residuals of leaching.

1. INTRODUCTION

Supported by the US Department of Energy, Brookhaven National Laboratory (BNL) is undertaking an experimental study on the treatment of CdTe photovoltaic glass waste. The interest in treating the waste streams from environmental concerns that cadmium poses health concerns. The Environmental Protection Agency (EPA) regulates its discharge, and therefore, before disposing of CdTe-bearing PV manufacturing waste or spent PV products, a treatment technology must be identified that meets stringent environmental regulations. Hence, the major objective of this study is to establish a methodology that can prevent any environmental damage caused by cadmium through the disposal of PV product wastes, and can generate environmentally friendly, clean glass. Another objective is to determine a practical and economical technology for recovering and recycling of cadmium and tellurium extracted from the PV modules

Research approach. Very little research data exists on treating CdTe-bearing PV manufacturing wastes [1,2,3]. Thermodynamic information on tellurium [6] and cadmium has shown the following: cadmium is soluble in acid media, and insoluble in neutral and slightly alkaline media; tellurium (IV) is sparingly soluble in acid media, insoluble in neutral media, and soluble in alkaline media; and, tellurium (VI) is soluble in acid media, and insoluble in alkaline media. Other studies show that telluride can be readily oxidized with hydrogen peroxide in acid media [4,5]. Here, our approach is to leach out cadmium and tellurium from CdTe-bearing PV glass using hydrogen peroxide in acid media, followed by electrolysis to separate cadmium from tellurium.

2. DESCRIPTION OF THE EXPERIMENTS

Test materials. Two forms of PV product samples were tested in this study: 1) Intact pieces measuring 2.5” by 12” cut from CdTe PV modules manufactured by First Solar L.L.C., Perrysburg, Ohio; 2) Various sized fragments of PV modules representative of manufacturing waste in the same facility. These fragments were produced by breaking “out of specs” modules in a hammer-mill.

The average composition of the metals in the intact pieces (w/o connectors), measured by mass balances in the manufacturing facility, is approximately 0.05 Cd wt%; 0.06 % Te wt%; and, 0.01 Cu wt%.

The composition of the PV module fragments is uncertain since they were produced from “out of specs” modules during the start-up of manufacturing. They were expected to contain, on average, more copper than the intact pieces because they include bus connections and likely were non-homogeneous.

Leaching Equipment. The leaching tests initially were carried out in beakers held in a water bath at a carefully controlled temperature. A mercury thermometer in the leach solution measured the temperature. The leach slurries were agitated by a motor-driven, Teflon-coated stirrer paddle. Samples of the solution were withdrawn periodically with a syringe to assess the leaching rate.

After preliminary tests, the experiments were continued at ambient temperature and more intense agitation. Subsequently, a tumbling machine was used that is designed for Toxicity Characteristic Leaching Procedure (TCLP) tests. PV fragments were mixed with certain amount of leaching agent in a plastic bottle and sealed, and then the bottles were put into the cages of the tumbling machine. Samples were withdrawn every 30 minutes, diluted with 5% HNO₃, and analyzed for cadmium, tellurium, and copper using a Varian Model Liberty 100 Inductively Coupled Plasma (ICP) spectrometer.

In a four tests (#33 to #36), a commercial paint-can shaker was used instead of the TCLP tumbler, to see whether the intensity of mixing affected leaching.

Procedures. We assessed the efficiency of two oxidative-leaching procedures in extracting cadmium and tellurium from PV glass; hydrogen peroxide leaching in sulfuric acid, and hydrogen peroxide leaching in hydrochloric acid. These experiments were done at two scales, with ~315 g of PV glass in small plastic bottles, and ~2153 g of PV glass in large plastic bottles. The pieces of intact PV glass were first carefully broken into smaller pieces with a hammer, and loaded into a plastic bottle. Fresh acid solutions, i.e., H₂SO₄ or HCl, were prepared containing aqueous H₂O₂ (30%) as an oxidizing agent, and a surfactant, C₈H₁₇SO₄Na were added. The concentration of acid ranged from 1.0 M to 4.0

M. To obtain a complete leaching profile, the tumbling machine was run for 48 hours, although the samples were withdrawn from time to time. The samples were then filtered through syringe filters with the pore size of 0.20 μm to 0.70 μm . The filtrate was diluted with 5% HNO_3 and the solutions were analyzed for cadmium, tellurium, and copper by ICP spectrometry.

Normalization method for the concentration of leaching solution. The concentration measurements from the ICP analysis were normalized to account for the dilution of the sample and depletion of the leaching solution during sampling, and were expressed as wt % of the PV sample used in each test. The following equation was used to normalize the concentrations of the leaching solutions:

$$C_I^{NORMALIZED} = C_I + \frac{b \times (C_1 + C_2 + C_3 + \dots + C_I - I \times C_I)}{a_0}$$

in which, $C_I^{NORMALIZED}$ is the normalized concentration of the leaching solution after I sampling;

C_I is the measured concentration of the leaching solution after I sampling.

C_1 is the measured concentration of the leaching solution after the first sampling

C_2 is the measured concentration of the leaching solution after the second sampling.

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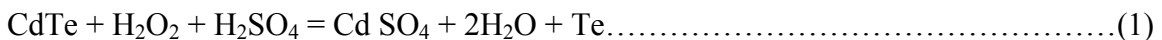
b is the amount of single sampling in grams

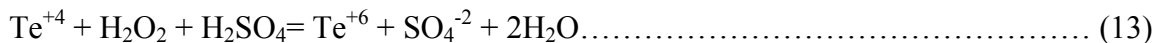
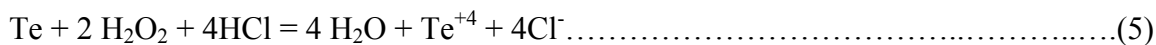
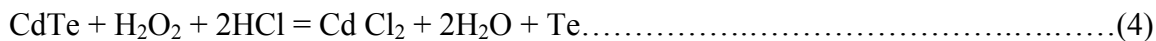
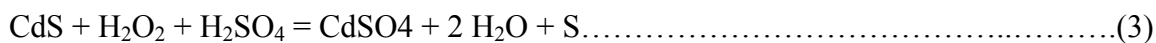
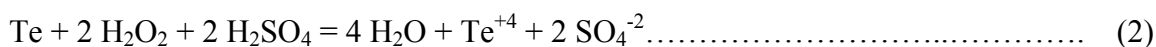
a_0 is the amount of initial leaching solution in grams

I is I^{th} sampling.

3. RESULTS

The preliminary tests showed that H_2O_2 readily oxidized both cadmium and tellurium in acid media. The leaching reactions can be expressed as follows [1,6,7]:





In strongly oxidizing conditions, tellurium may be oxidized to the hexavalent form, Te^{+6} , according to reaction (13). Consequently, it is likely that the solutions may contain tellurium in both the tetravalent and hexavalent states, depending on the oxidizing conditions.

The major parameters describing these tests are summarized in Table 1, below.

TABLE 1. EXPERIMENTAL PARAMETERS					
Test	Raw material	Leaching acid and concentration	Oxidizing agent mL-H ₂ O ₂ /kg-glass (RO)	Ratio of liquid to glass ⁺	
				kg-liquid/kg-glass ⁺ (R)	mL-liquid/kg-glass ⁺
#11	intact PV module	4.0 M HCl	12.6	0.54	473
#12	intact PV module	2.0 M HCl	12.6	0.54	473
#13	intact PV module	1.0 M HCl	12.7	0.51	474
#14	intact PV module	4.0M H ₂ SO ₄	12.7	0.62	476
#15	intact PV module	2.0M H ₂ SO ₄	12.8	0.59	478
#16	intact PV module	1.0M H ₂ SO ₄	12.8	0.55	480
#17	intact PV module	1.0 M HCl	4.7	0.53	475
#18	intact PV module	1.0 M HCl	8.0	0.53	479
#19	intact PV module	1.0M H ₂ SO ₄	4.8	0.55	484
#20	intact PV module	1.0M H ₂ SO ₄	7.9	0.57	476
#21	PV module fragments	2.0M H ₂ SO ₄	12.5	0.50	479
#22	PV module fragments	1.0M H ₂ SO ₄	12.5	0.49	479
#23	intact PV module	1.0M H ₂ SO ₄ , used*	12.8	0.61	532
#24	intact PV module	1.0M H ₂ SO ₄ , used*	6.3	0.61	524
#25	PV module fragments	2.0M H ₂ SO ₄	7.9	0.53	501
#26	PV module fragments	1.0M H ₂ SO ₄	7.9	0.51	481
#27	intact PV module	1.0M H ₂ SO ₄ , used 2x*	6.4	0.82	709
#28	PV module fragments	3.2M H ₂ SO ₄	12.0	0.27	231
#29	PV module fragments	2.0M H ₂ SO ₄	11.5	0.26	235
#30	PV module fragments	2.0M H ₂ SO ₄	5.7	0.25	228
#31	PV module fragments	1.0M H ₂ SO ₄	11.4	0.24	234
#32	PV module fragments	1.0M H ₂ SO ₄	5.7	0.24	228
#33	PV module fragments	3.2M H ₂ SO ₄	12.0	0.27	231
#34	PV module fragments	2.0M H ₂ SO ₄	11.4	0.26	234
#35	PV module fragments	2.0M H ₂ SO ₄	5.7	0.25	228
#36	PV module fragments	1.0M H ₂ SO ₄	11.4	0.24	234
#37	PV module fragments	1.0M H ₂ SO ₄	5.7	0.24	228
#38	PV module fragments	1.0M H ₂ SO ₄	11.5	0.51	488

⁺ “glass” denotes the entire PV module pieces, which comprise about 99% glass.

* “Used” means used once before

“Used 2x” means used two times before

Tests with intact PV glass pieces. Leaching of intact PV glass pieces was tested with different sulfuric acid/hydrogen peroxide and hydrochloric acid/ hydrogen peroxide solutions. Our experiments showed that, at the same strength, sulfuric acid extracted

somewhat more cadmium and tellurium. Figures 1 and 2, respectively, show the first four hours' extraction profiles for Cd and Te (tests # 11-20). .

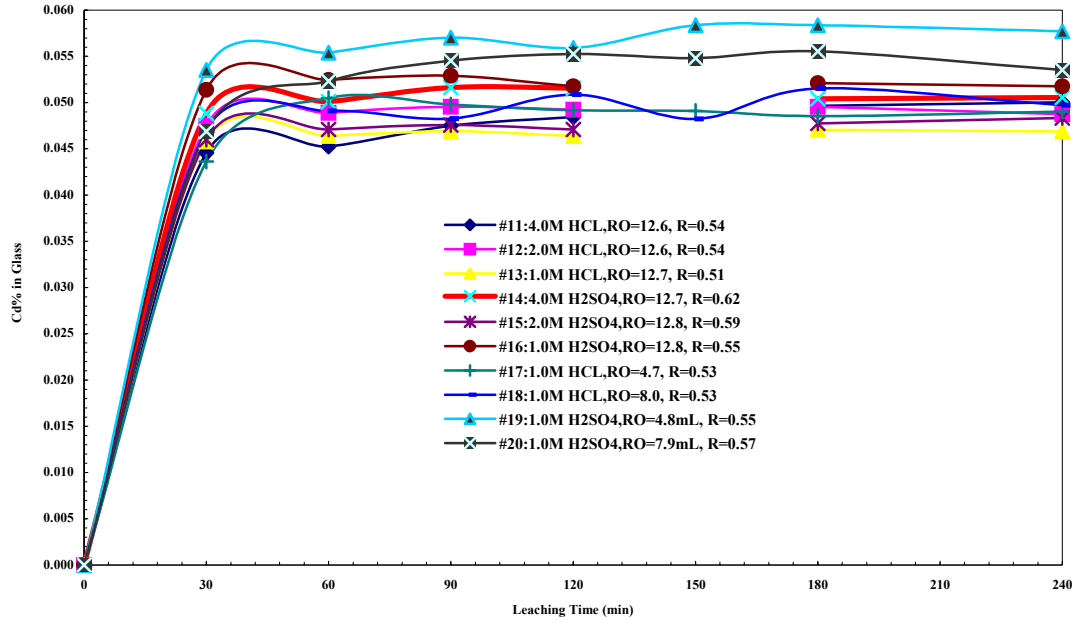


Figure 1. Cd Leaching Experiments #11-#20. RO-ratio of H_2O_2 to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

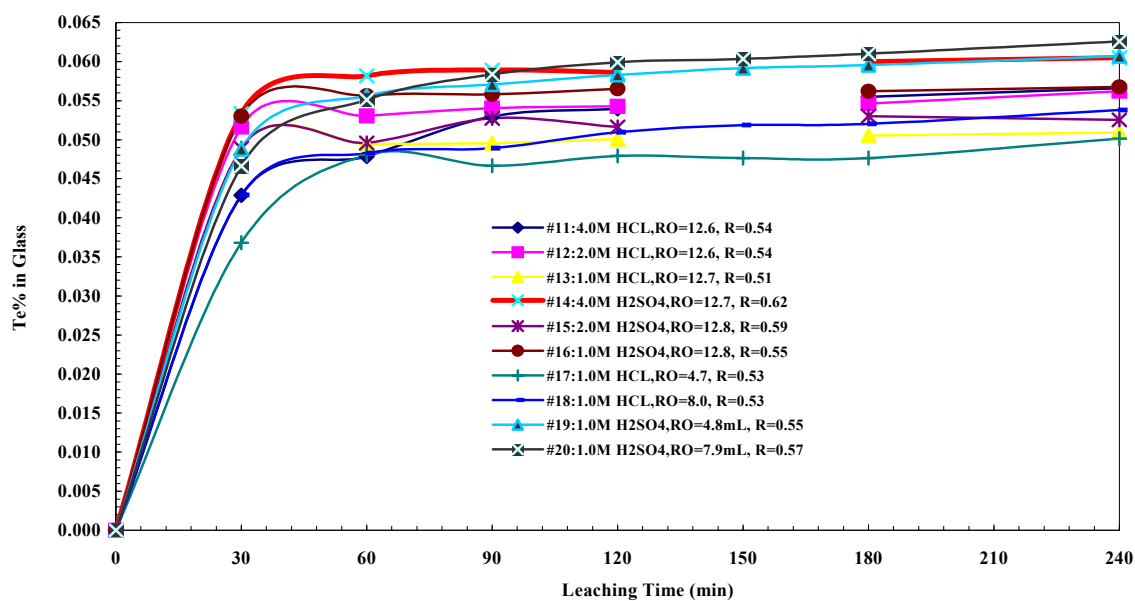


Figure 2. Te Leaching Experiments #11-#20. RO-ratio of H_2O_2 to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

Figures 1 and 2 show that the sulfuric acid-based tests #16, #19, and #20 best leached Cd. The liquid/ glass ratios of these tests (R) were around ~ 0.54 kg liquid per kg glass (~ 480 mL-liquid/kg-glass); the ratios of hydrogen peroxide (RO) added to the leaching agent, 1.0M sulfuric acid, were 12.8, 4.8, and 7.9 mL- H_2O_2 /kg-glass for tests #16, #19, and #20, respectively. This suggests that a higher strength acid may not be advantageous for leaching cadmium as anticipated. Most of the tests revealed that in the first 30 minutes, cadmium was more readily attacked and leached out into solution than tellurium. Thus, at the 30-minute point, more than 80% of cadmium and tellurium were transferred from the glass into solution. However, stronger sulfuric acid initially appears to leach Te quicker than a weaker solution, as shown in Figure 2. During the first 90 minutes, the leaching of tellurium with 4.0M of sulfuric acid was the highest among all tests, but with longer times (i.e., >2 hr) the 1 M acidic solution became equally effective as the 4 M one. No further studies were made of hydrochloric acid leaching because its efficacy at extracting cadmium and tellurium was poorer than that of sulfuric acid, and furthermore, hydrochloric acid is more volatile. We note that ICP analysis of the solutions showed

that trace amounts of copper exists in intact PV glass. The extraction of copper was quantified in later tests.

The efficiency of reused sulfuric acid also was tested to assess the possibility of recycling the leaching agent. These results are shown in tests #23, #24, and #27. The first two solutions were obtained by mixing the filtered used solutions from tests #16, #19, and #20, and adding a small amount of make-up H_2O_2 . (The amount of hydrogen peroxide added to #23 and #24 differed, as seen from Table 1). In Test #27 the leaching solution already was used twice; it was a mixture of the filtrate from #23 and #24. Figures 3 and 4 reveal that the reused solutions were slightly less effective than unused ones. A once-used solution was about 10% less effective than the original in leaching Cd, and 3% less effective in leaching Te. The twice-used solution was about 15% less effective in leaching both metals. Nevertheless, these results demonstrate that leaching solutions can be reused after adding the appropriate makeup H_2O_2 , thereby minimizing the production of liquid waste. The measured concentrations of reused leaching solutions are listed in Table 2.

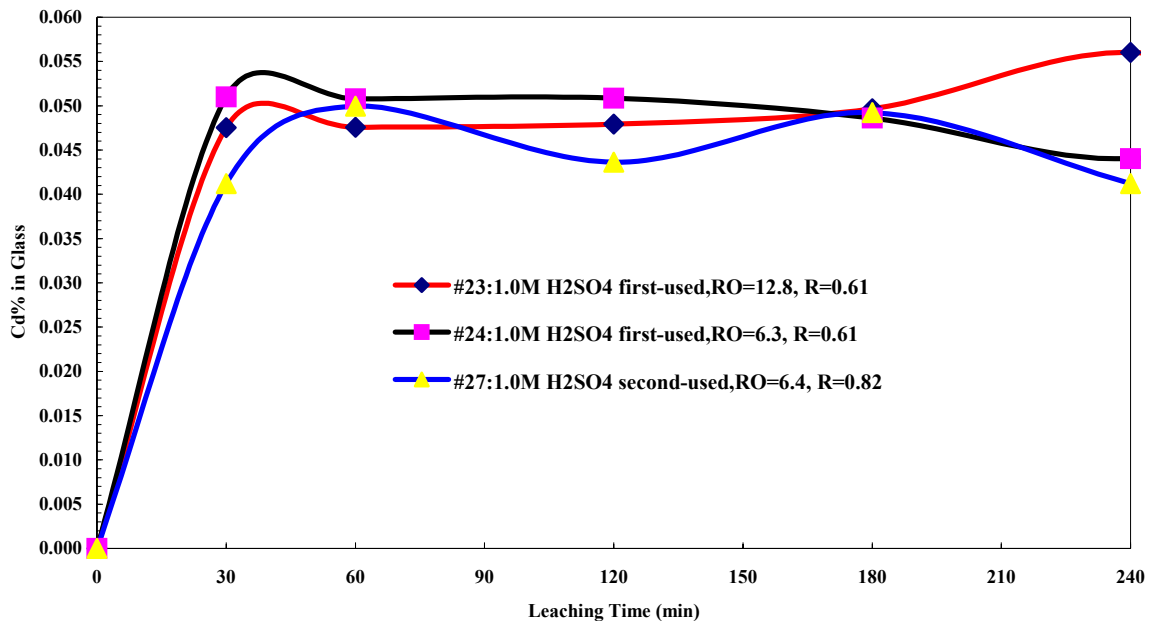


Figure 3. Cd Leaching Experiments #23,#24,#27. RO-ratio of H_2O_2 to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

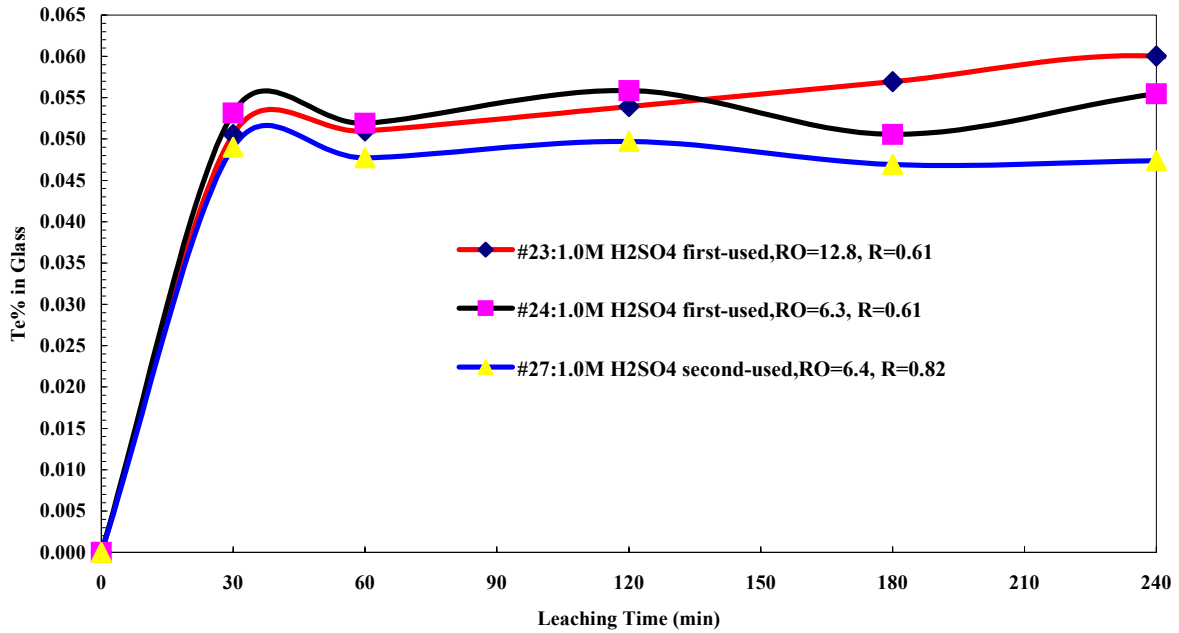


Figure 4. Te Leaching Experiments #23,#24,#27. RO-ratio of H₂O₂ to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

Table 2. The Concentration of Reused Leaching Agent

	#23 Normalized Results		#24 Normalized Results		#27 Normalized Results	
Leaching	1.0M H ₂ SO ₄ re-used, RO=12.8		1.0M H ₂ SO ₄ re-used, RO= H ₂ O ₂		1.0M H ₂ SO ₄ Re-used 2x, RO=6.4	
Time	PPM	PPM	PPM	PPM	PPM	PPM
(min)	Te	Cd	Te	Cd	Te	Cd
0 (Initial)	1080.31	979.54	1080.31	979.54	1998.84	1759.63
30	1904.40	1753.93	1953.20	1816.94	2598.00	2263.59
60	1910.84	1754.39	1932.38	1813.00	2582.73	2370.52
120	1959.33	1760.59	1997.59	1814.33	2606.88	2293.07
180	2061.51	1830.80	1977.07	1748.96	2572.48	2361.45
240	2106.09	1891.08	2007.19	1799.88	2578.12	2263.50
300	1964.72	1770.25	2047.31	1811.45		
420					2547.00	2215.31
1080	2108.77	1867.85	2115.57	1828.44		
1440	2089.08	1892.95	2009.78	1804.56	2539.65	2222.82
2880					2674.41	2322.94

As shown in Table 2, after two consecutive leaching procedures, the solution contained ~2.5 g/L of tellurium and ~2.2 g/L of cadmium.

Tests with PV fragments. The PV fragments contained copper in bus connections and in the CdTe layer. Therefore, we also analyzed the leaching solution for copper using ICP. The copper was in elemental form, and, consequently, consumed hydrogen peroxide during leaching, as shown in Reaction 7, and accordingly made it necessary to add H₂O₂ makeup solution. In these experiments we also examined the effect of varying the volume of leaching solution used for treating a constant mass of PV fragments. In one series of tests (#21, #22, #25, and #26), the ratio of liquid to solid was fixed around ~480 mL-liquid/kg-solid (i.e., 0.5 kg-liquid/kg-solid). In other tests (#28 through #32), the ratio was around ~230 mL-liquid/kg-glass (i.e., 0.25 kg-liquid/kg-solid).

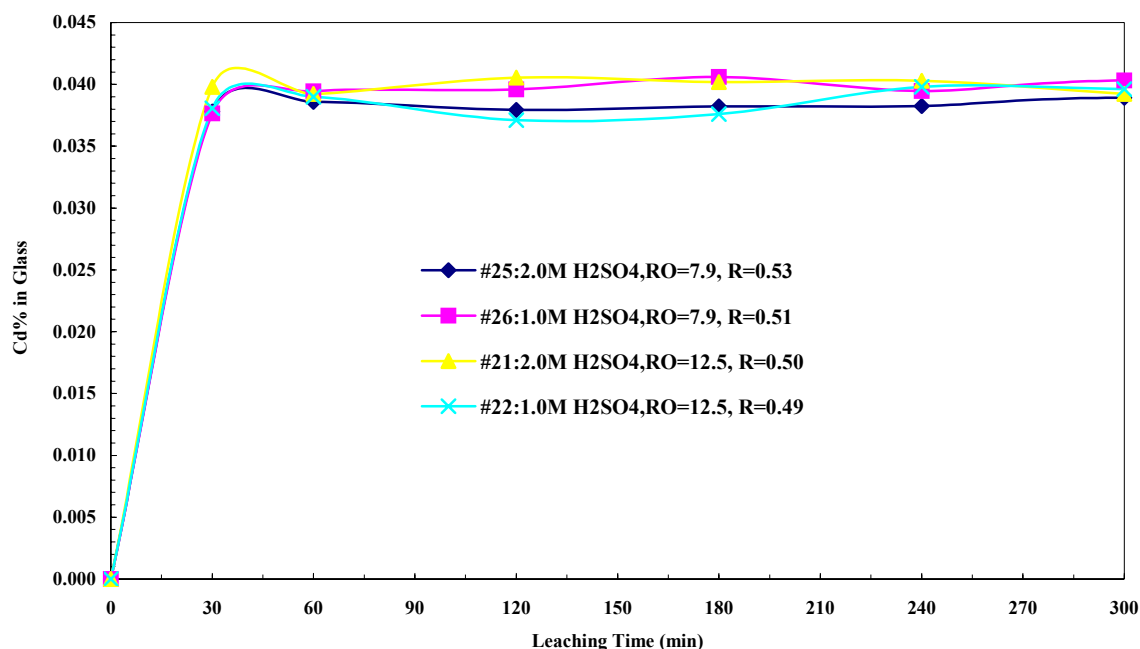


Figure 5. Cd Leaching Experiments #21,#22,#25,#26. RO-ratio of H₂O₂ to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

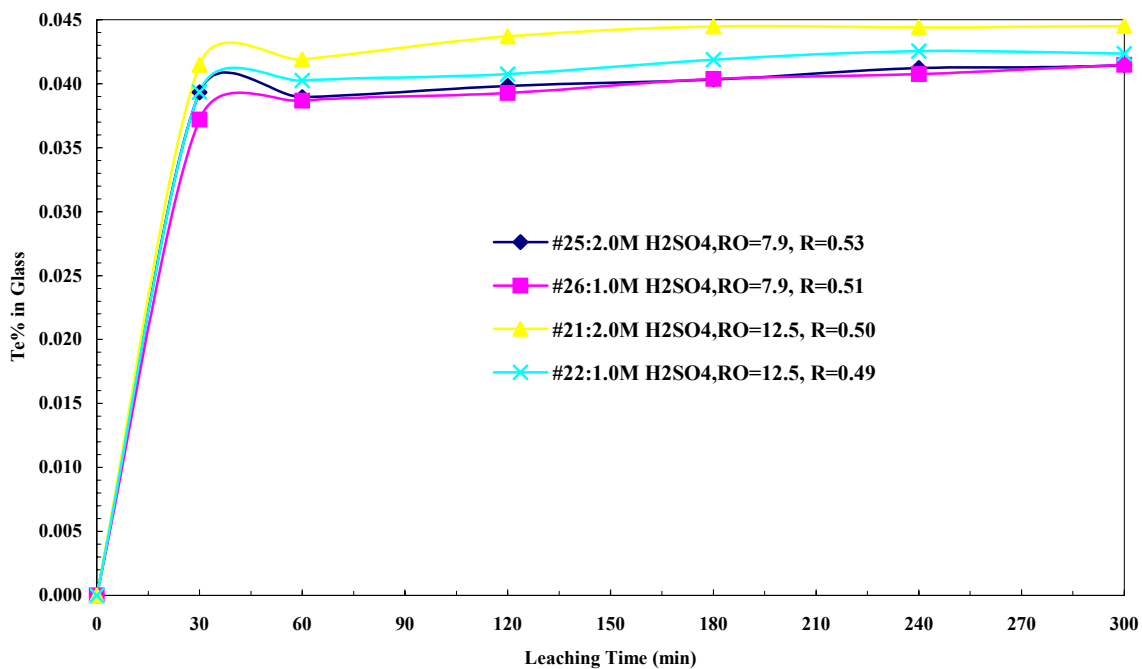


Figure 6. Te Leaching Experiments #21,#22,#25,#26. RO-ratio of H₂O₂ to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

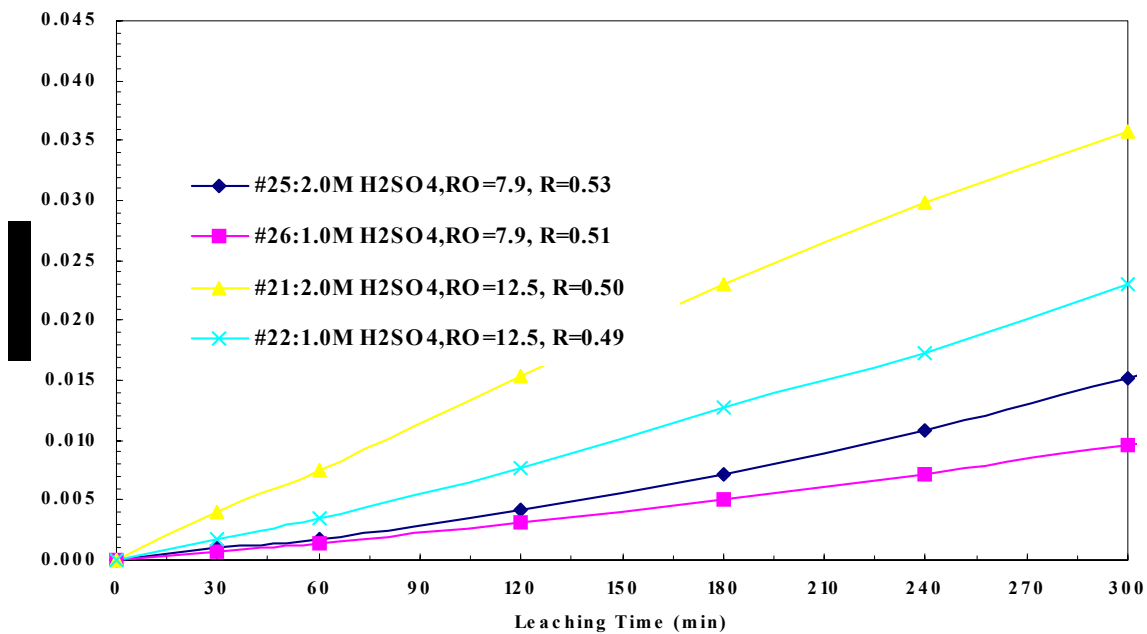


Figure 7. Cu Leaching Experiments #21,#22,#25,#26. RO-ratio of H₂O₂ to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

Figures 5, 6, and 7, respectively, depict the dissolution of cadmium, tellurium, and copper as function of processing time with the liquid/solid ratio of ~ 0.5 kg-liquid/kg-PV-fragments. As shown in Figures 5 and 6, the concentration of cadmium and tellurium in solution does not change appreciably after 30 minutes, suggesting that their leaching was completed within this interval. However, the dissolution of copper increases linearly with within the first 300 minutes (Figure 7), and apparently, was not complete by then. In terms of the percentage of tellurium extracted, 2.0M of sulfuric acid with 12.5 mL- H_2O_2 /kg-glass appears to be the best among the four tests. For extraction of cadmium 2.0 M of sulfuric acid seems to be not much better than 1.0 M of sulfuric acid. More tests are needed, based on intact, uniform concentration PV samples, to confirm this observation. Should this be the case, the weaker acid would be preferred because of its advantages in cost, safety, and waste reduction. Comparison of Figures 1 and 2 with Figures 5 and 6, respectively, shows that the percentage of cadmium and tellurium extracted from intact PV pieces is considerably higher than that extracted from the PV fragments. This is not surprising, given the expected variability in concentrations in the large quantity (400 lb, 55-gal drum) of PV fragments supplied.

The liquid/solid ratio of $\sim 230\text{mL}$ -liquid/kg-glass also was explored in tests #28 through 32. These tests used one-half the solution-to-glass ratio (R) than the previous ones. Due to the low ratio of liquid/solid, withdrawing samples from these solutions was almost impossible in the first 300 minutes since very little free liquid phase was created. Therefore, the first sample was taken after 300 minutes of continuous leaching. The results are shown in Figures 8, 9 and 10 respectively.

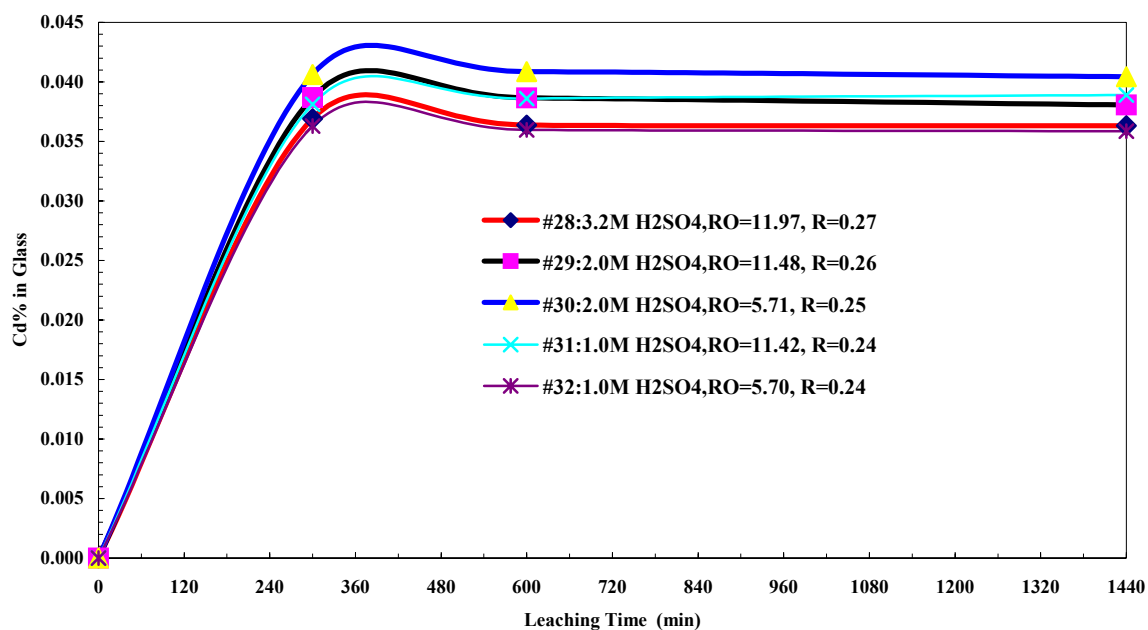


Figure 8. Cd Leaching Experiments #28,#29,#30,#31,#32. RO-ratio of H_2O_2 to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

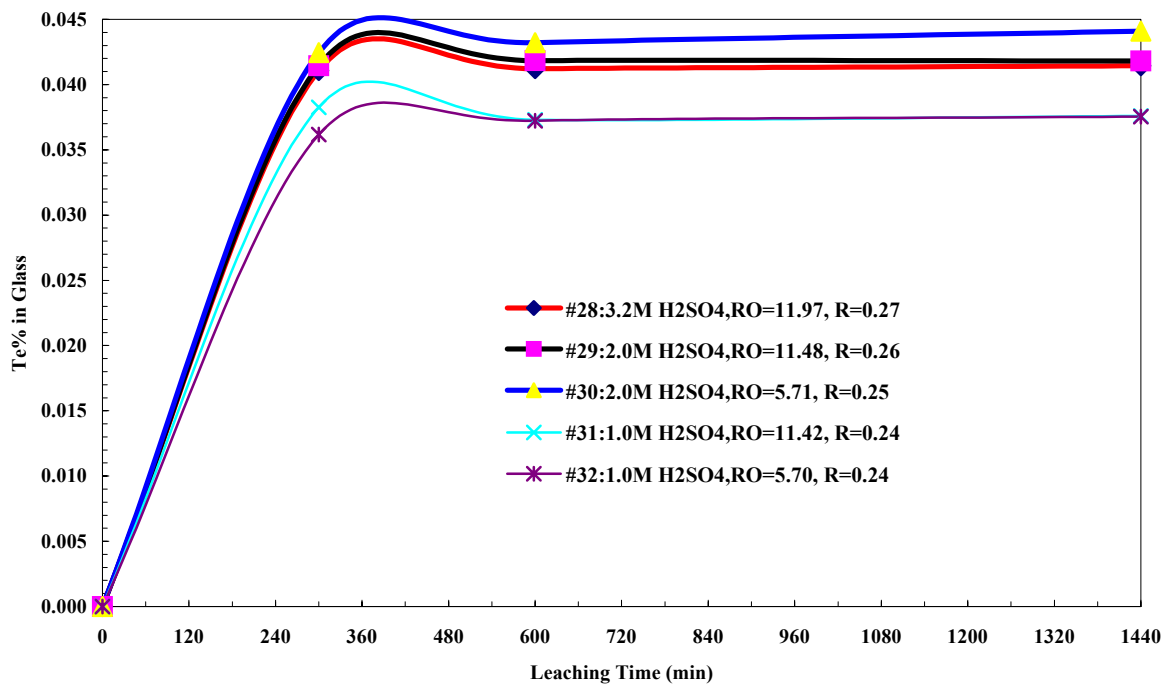


Figure 9. Te Leaching Experiments #28,#29,#30,#31,#32. RO-ratio of H_2O_2 to glass(mL/kg); R-ratio of leaching solution to glass (kg/kg)

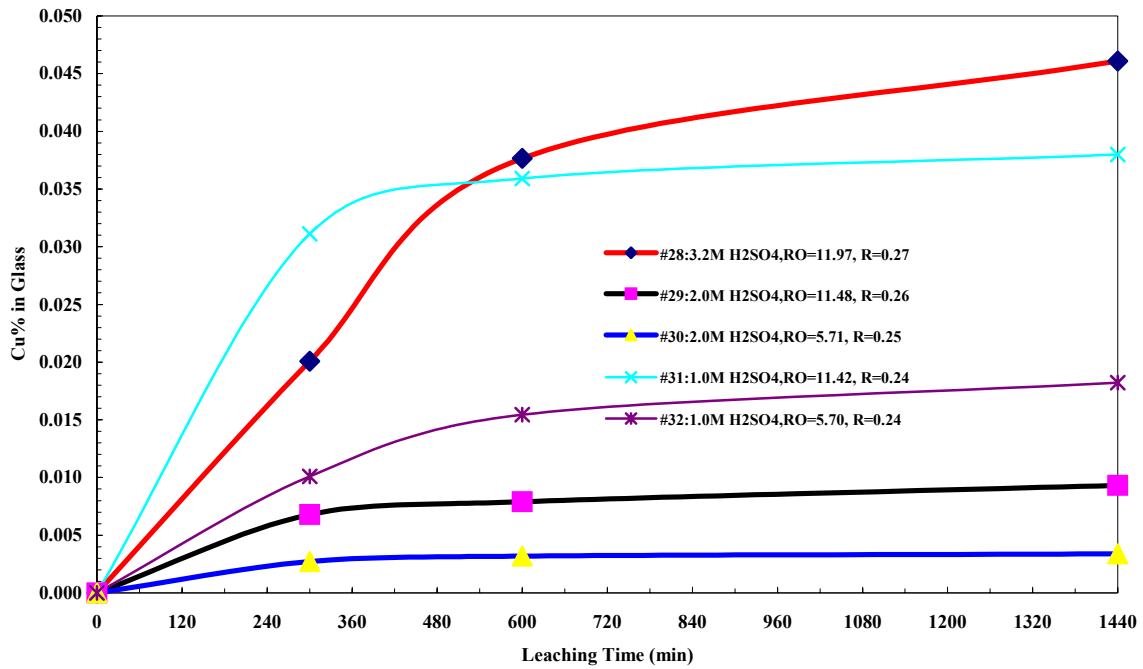


Figure 10. Cu Leaching Experiments #28,#29,#30,#31,#32. RO-ratio of H₂O₂ to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

Tests with the low ratio of liquid/solid showed that 2.0 M of sulfuric acid was better than 1.0 M sulfuric acid in extracting tellurium. The best leaching agent for cadmium was 2.0 M of sulfuric acid and 5.7 mL-H₂O₂/kg-glass. The percentage of cadmium in PV glass ranges from 0.036% to 0.041% and tellurium from 0.036% to 0.044%.

As in the previous experiments, copper was leached much slower than cadmium and tellurium, and it was not completed within the leaching times we employed. We note, however, than the concentration of copper in the module is much lower than all applicable waste-classification standards, including the California TTLC. The latter and the concentration of Cu and Cd in the CdTe PV module are shown below.

Element	California TTLC (g/kg)	Module Content (g/kg)
Cu	2.5	0.57(including both CuCl ₂ and Cu foil connections)
Cd	0.1	0.69

Figures 11,12, and 13 plot the results of leaching tests with a commercial paint-can shaker (#s 33-38). The leaching time for each test was five hours during which three samples were taken for ICP analysis of cadmium, tellurium, and copper.

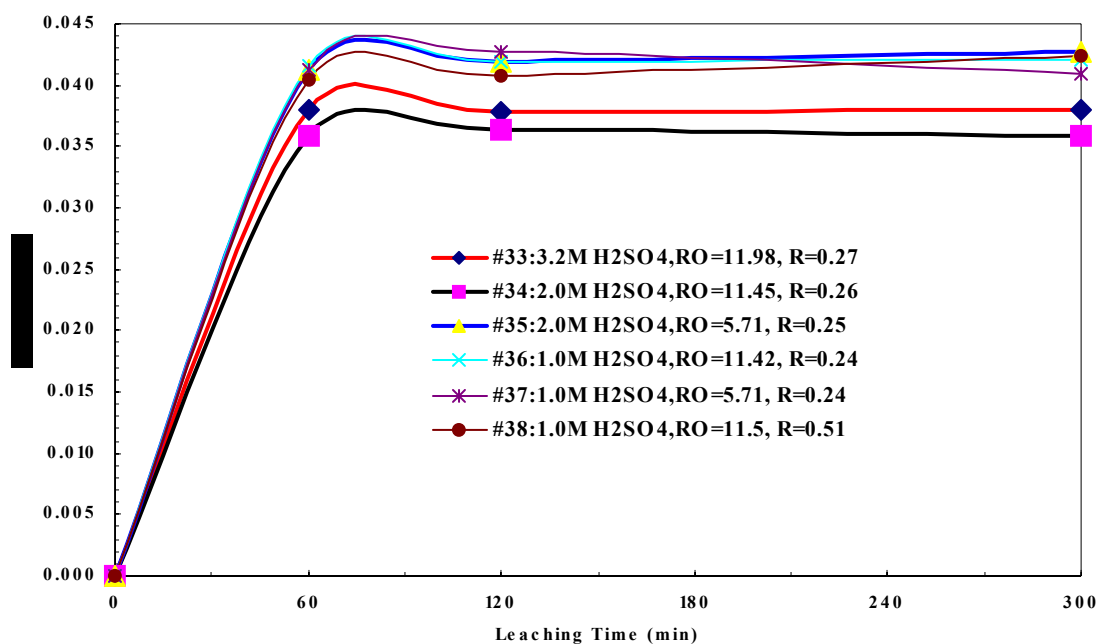


Figure 11. Cd Leaching Experiments #33-#38. RO-ratio of H₂O₂ to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

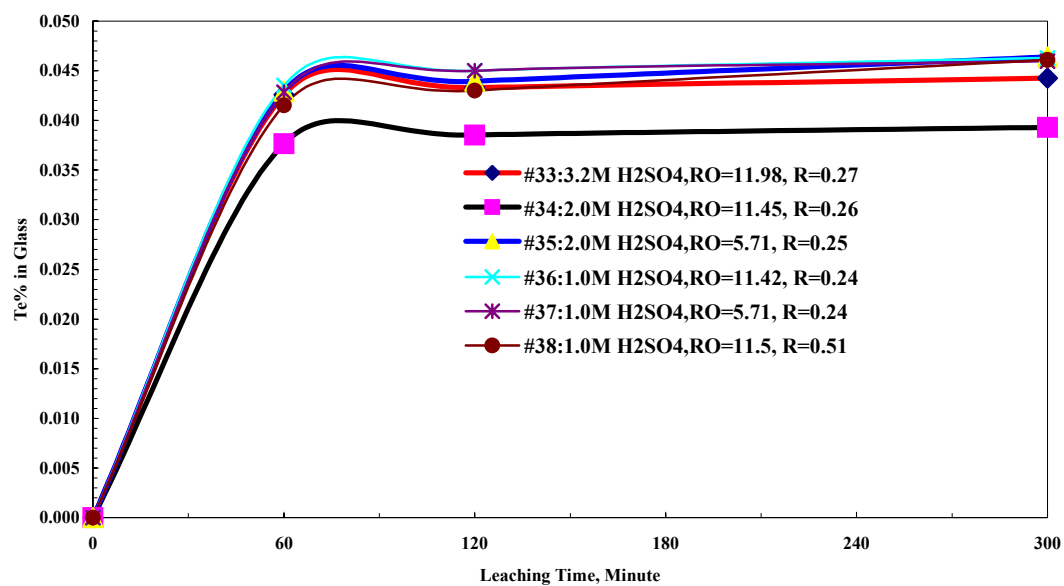


Figure 12. Te Leaching Experiments #33-#38. RO-ratio of H₂O₂ to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

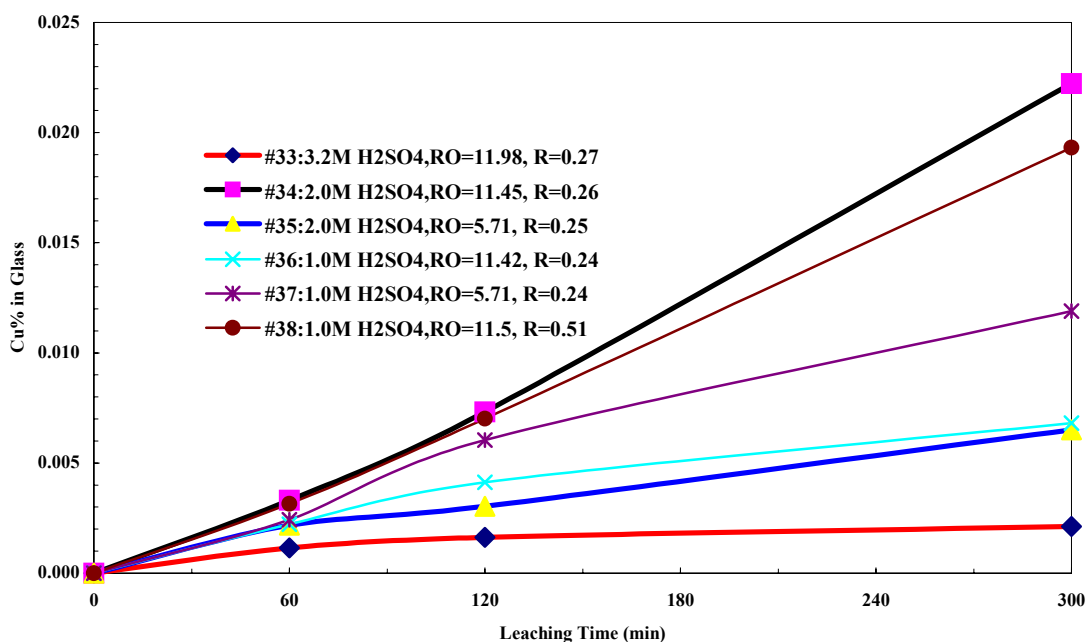


Figure 13. Cu Leaching Experiments #33-#38. RO-ratio of H₂O₂ to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)

The leaching rate of cadmium and tellurium was much faster than that of copper, especially in the first hour. Without exception, the concentration of copper in the leaching agent was less than 10% of that of cadmium and tellurium. Apparently, cadmium and tellurium can be selectively removed by carefully controlling leaching time, thus, preventing copper from being transferred into solution. This is an important finding because, otherwise, copper would cause problems in the following step of separating cadmium from tellurium. Surprisingly, a higher concentration of sulfuric acid did not necessarily entail a higher leaching efficiency of cadmium and tellurium, as Figures 11 and 12 demonstrate. Figure 11 shows that leaching with 3.2 M of H₂SO₄ was the least efficient. On the other hand, 1.0 M of H₂SO₄ was the best at leaching cadmium.

We observed, from all leaching tests, that the ratio of tellurium to cadmium in the PV module glass is less than the stoichiometric ratio of 1.135 in the CdTe molecule, which is explained by the substitution of Cd for Cu in the molecular structure. On the other hand, cadmium is also present in CdCl₂ and CdS, whereas tellurium is present only in CdTe. Based on the concentrations of cadmium and tellurium in the leaching solutions, all

experiments had weight ratios of tellurium to cadmium between 1.0 and 1.135, and particularly, in the first 30 minutes, the leaching rate of cadmium was faster than that of tellurium. This difference can be seen from Figures 14 and 15 in the processing time range of 30 minutes to 240 minutes. Figure 14 displays the results of leaching of intact PV module glass, while Figure 15 shows those from PV module fragments.

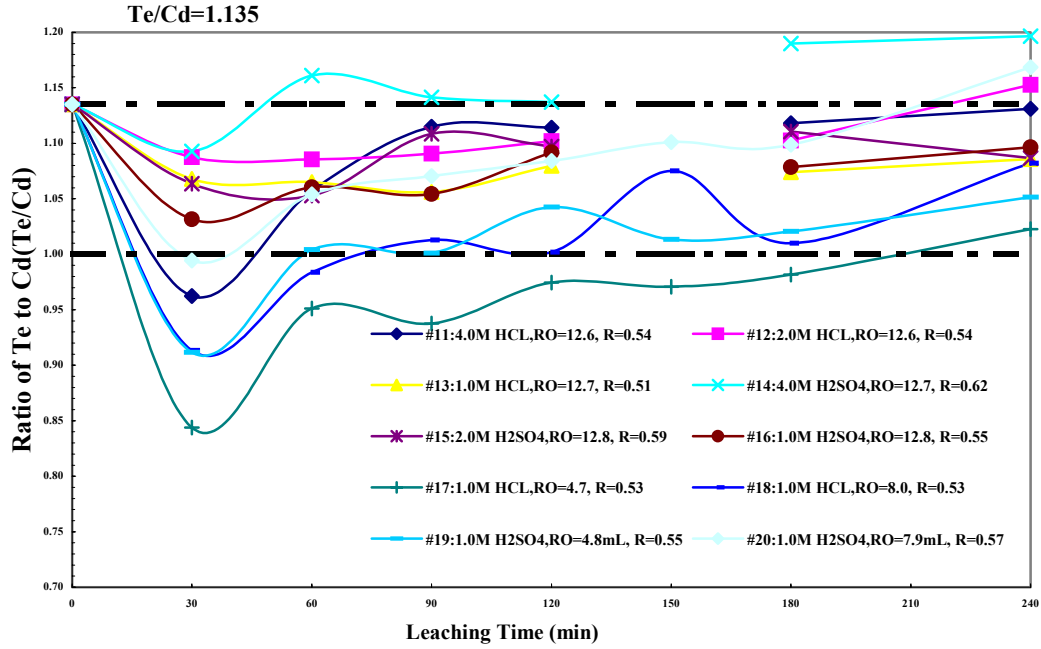


Figure 14. The ratio of Te to Cd in the intact PV module glass

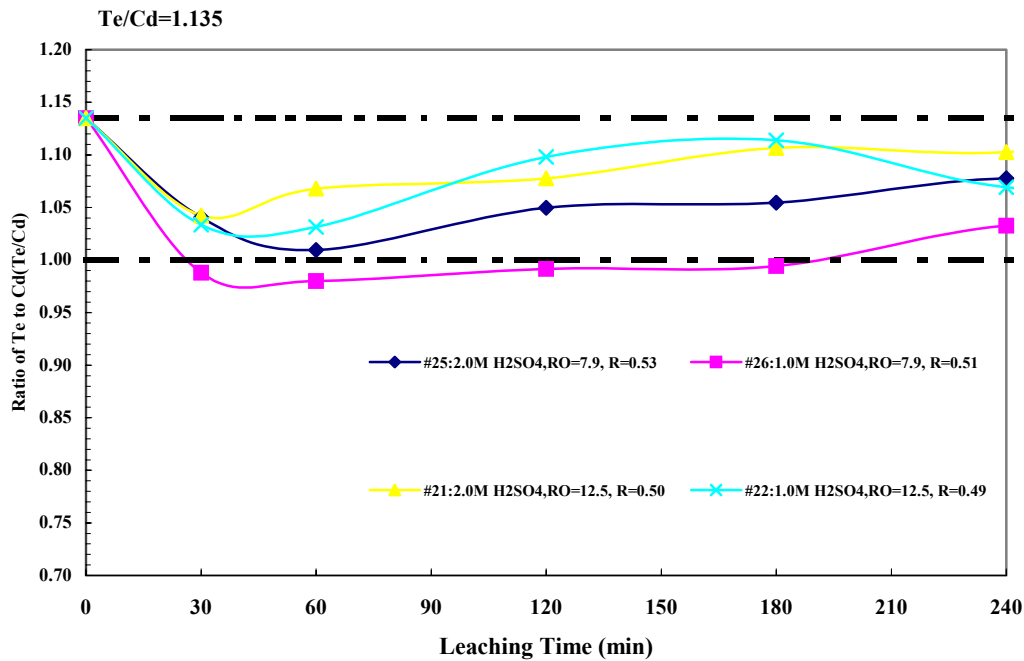


Figure 15. The ratio of Te to Cd in the PV module glass fragments

4. UNCERTAINTY ANALYSIS

The uncertainties considered in this experimental study relate to 1) The composition of the PV sample, 2) the composition of the leaching solution , 3) the leaching solution's weight and volume, 4) the volume of the sample taken for analysis, and, 5) the accuracy of the ICP measurements.

The PV samples were weighed before and after crushing; approximately 1% weight was lost due to fine residual or airborne particles. This loss most likely comprised glass fines produced by the impact of the hammer on the glass sheets of the PV “sandwich”. The normalized data given in this report account for this 1% loss of mass.

The reported compositions of the different leaching solutions are approximate, carrying an error due to measuring volumes in graduated cylinders. However, the total weight of the solution used was accurately determined with an OHAUS (Model E0D120, accurate

to 0.01g) scale. No quantifiable error is expected during the preparation of the leaching solution .

Samples of approximately 2 mL were withdrawn for analysis from a well-mixed liquid phase. They were first filtered, then their weights accurately measured with a Sartorius analytical balance (Model CP225D, accurate to 0.00001g). The measured samples were diluted with known amounts of 5% HNO₃ (25mL with their weights measured with Sartorius analytical balance). Such measurements have an inherent uncertainty of 0.001%, according to manufacturers data.

The error of the ICP analysis was determined by frequent calibration to be equal to, or less than .5% (calibration was performed after every eighth measurements). The results of calibration are shown in Appendix B. Several measurements were repeated and the results were always reproduced within 5%.

Since the above uncertainties are likely to be independent ones, , the overall uncertainty of the results is believed to be within 5%.

5. CONCLUSION and RECOMMENDATIONS

We demonstrated that Cd and Te can be effectively leached from fragments of PV modules with a dilute solution (i.e., 1.0 M) of H₂SO₄ and ~5.0 mL H₂O₂ per kg of PV fragments. Using a dilute solution has obvious cost-, safety-, and waste-management advantages over the 3.2 M H₂SO₄ /12 mL H₂O₂ per kg solution currently used by First Solar, L.L.C. (FS). However, in our small-scale experiments we had to use approximately twice as much leaching solution as the FS process to obtain a sufficient volume for multiple sampling of the liquid phase.

The dilute leaching solutions were reused once with relatively small loss of efficiency; reuse for second time resulted in a 15% loss of efficiency. We added a small quantity of oxidizer makeup solution before every reuse. Similarly, adding more acid could reduce

the loss of leaching efficiency. A leaching solution with tellurium of 2.6g/L and cadmium of 2.3g/L was obtained by such a consecutive leaching procedure.

Under the same molar concentration, the leaching efficiency of sulfuric acid was better than that of hydrochloric acid.

Copper was incompletely leached in the experiments performed so far. The rate of copper leaching was especially limited in the first three hours. Therefore, cadmium and tellurium might be selectively removed by controlling the leaching time, thus leaving copper in the glass phase. This approach is environmentally acceptable since the concentration of copper in the module is much lower than all applicable waste classification standards, including the California TTLC. Preventing or reducing Cu extraction, might allow a better separation of cadmium from tellurium in the liquid phase.

In the second phase of this study we will quantitatively separate and recover all cadmium from the liquid phase. The recovery of tellurium and copper is of secondary importance, as these metals do not generate a “waste” classification.

6. REFERENCES

1. Tolley William K. and Palmer Glenn R., Recovering Cadmium and Tellurium From Thin-Film Photovoltaic Device Scrap. United States Bureau of Mines, Government Report, I 28.23:9588 (RI 9588), 1995.
2. Fthenakis Vasilis M., End-of-Life Management and Recycling of PV Modules, Energy Policy 28(2000) 1051-1058.
3. Vasilis M. Fthenakis and Moskowitz P.D., The Value and Feasibility of Proactive Recycling, NCPV Program Review Meeting, Sep. 8-11, 1998, Denver CO, (AIP) Conference Proceedings 462, (Editor, Al-Jassim et al.), Pp. 332-337, American Institute of Physics, Woodbury, NY, 1999.
4. Bohland John, Todd Dapkus, Kristin Kamm and Ken Smigielski, Solar Cells, Inc., Photovoltaics As Hazardous Materials; The Recycling Solution. Date?

5. Malinowska B., Rakib M. and Durand G., Cadmium Recovery and Recycling from Chemical Bath Deposition of CdS Thin Layers, Progress in Photovoltaics: Research and Applications. 2002; 10:215-228.
6. Cooper W. Charles, Tellurium, Van Nostrand Reinhold Company, New York, 1971.
7. Chizhikov D. M., Cadmium, Pergamon Press Ltd., New York, 1966

APPENDIX A: SCALE OF EXPERIMENTS						
Exp. #	Total Processing Time	Original Glass Amount	Original Solution Amount		H ₂ O ₂ Amount	Surfactant Amount
	hours	gram	mL	gram	mL	mL
#11	48	317.37	150	170.42	4.00	0.64
#12	48	317.01	150	171.11	4.00	0.64
#13	48	316.16	150	159.95	4.00	0.64
#14	48	315.12	150	196.26	4.00	0.64
#15	48	313.63	150	185.00	4.00	0.64
#16	48 hours	312.26	150	172.14	4.00	0.64
#17	24 hours	315.99	150	167.92	1.50	0.64
#18	24 hours	313.45	150	166.55	2.50	0.64
#19	24 hours	309.89	150	170.62	1.50	0.64
#20	24 hours	314.87	150	178.97	2.50	0.64
#21	24 hours	2153.77	1031	1066.93	27.00	4.266
#22	24 hours	2153.99	1031	1058.89	27.00	4.266
#23	24 hours	312.10	166	191.54	4.00	none added
#24	24 hours	316.56	166	192.82	2.00	None added
#25	48 hours	2154.91	1080	1152.69	17.00	4.266
#26	48 hours	2153.76	1037	1098.51	17.00	4.266
#27	48	313.13	222	256.05	2.00	0.64
#28	24	315.70	73	86.73	3.78	0.63
#29	24 hours	314.80	74	81.29	3.61	0.63
#30	24 hours	315.40	72	78.53	1.80	0.63
#31	24 hours	316.31	74	76.98	3.61	0.63
#32	24 hours	315.72	72	75.46	1.80	0.63
#33	5 hours	315.46	73	84.09	3.78	0.63
#34	5 hours	315.57	74	81.63	3.61	0.63
#35	5 hours	315.50	72	79.77	1.80	0.63
#36	5 hours	316.25	74	77.35	3.61	0.63
#37	5 hours	315.51	72	75.98	1.80	0.63
#38	5 hours	315.44	154	159.45	3.61	0.63

Appendix B: Error of ICP analysis

Date ICP Performed	ICP #	Measurements of Standard Solutions						Comments
		Cd			Te			
		Nominal PPM	Measured PPM	Error %	Nominal PPM	Measured PPM	Error %	
12/05/03	10	50.00	46.88	-6.24	50.00	48.89	-2.22	Cd and Te of #11 through #16
		20.00	19.25	-3.75	20.00	19.30	-3.50	
		20.00	19.46	-2.70	20.00	19.08	-4.60	
		10.00	9.83	-1.69	10.00	9.48	-5.16	
		100.00	94.33	-5.67	100.00	98.42	-1.58	
		20.00	19.36	-3.20	20.00	19.32	-3.40	
		0.00	0.00	#####	0.00	0.00	#####	
12/11/03	11	50.00	48.82	-2.36				Cd of #11 through #16 Glasswool of #6, #8 Te was not measured
		20.00	19.30	-3.50				
		100.00	95.40	-4.60				
		10.00	9.73	-2.68				
		100.00	95.80	-4.20				
		50.00	48.26	-3.48				
		100.00	93.20	-6.80				
12/15/03	12	50.55	50.56	0.02	50.60	50.29	-0.61	Glasswool of #6, #8
12/16/03	13	9.93	9.61	-3.24	10.07	9.52	-5.51	Cd and Te of #17 through #20
		20.04	21.08	5.19	20.30	20.85	2.70	
		39.91	41.75	4.61	40.65	42.62	4.86	
		20.04	20.32	1.40	20.30	20.59	1.42	
12/17/03	14	40.65	40.56	-0.21	40.65	41.70	2.60	Cd and Te of #11 through #16 24-hour leaching and before 24-hour leaching
		9.93	9.88	-0.52	10.07	9.92	-1.48	
		100.00	92.12	-7.88	100.00	97.76	-2.24	
Date ICP Performed	ICP #	Measurements of Standard Solutions						Comments
		Cd			Te			
		Nominal PPM	Measured PPM	Error %	Nominal PPM	Measured PPM	Error %	
12/21/03	15	10.05	10.19	1.39	10.19	9.67	-5.02	Cd and Te of #21 and #22 Cd and Te of #11 through #16 of 48-hour leaching Glasswool of #5, #7, and #4
		19.88	19.76	-0.61	20.33	20.09	-1.18	
		99.51	98.75	-0.77	101.13	103.60	2.44	
		40.17	40.46	0.71	40.83	40.94	0.26	
12/22/03	16							Cu of #21and #22
12/29/03	17	10.06	9.85	-2.10				Cd and Cu of #11 through #16 of before 24hrs, 24hrs, and 48 hrs results #17 through #20 of 24 hrs results
		19.80	19.00	-4.03				
		40.08	38.63	-3.62				
		19.80	20.22	2.14				
		10.06	10.17	1.12				
		40.08	39.61	-1.17				
01/04/04	18	19.88	19.34	-2.73	20.33	19.61	-3.54	Cd,Te of #23 and #24 Cu was not measured
		99.51	99.60	0.09	101.13	102.90	1.75	
		40.17	40.67	1.23	40.83	40.74	-0.23	
		19.88	19.57	-1.57	20.33	19.76	-2.80	
		10.05	9.94	-1.12	10.19	9.86	-3.17	
01/09/04	19							Cu of #25, #26 Cu of #21 and #22 of 24hrs plus 48-hrs leaching
01/12/04	20	0.00	0.01		0.00	0.18		Cd and Te of #25, #26 Cd and Te of #21 and #22 of 24hrs plus 48-hrs leaching
		99.51	96.71	-2.82	101.13	100.80	-0.33	
		19.26	19.73	2.44	19.45	19.49	0.20	
		40.17	41.06	2.21	40.83	41.33	1.22	
		10.12	10.15	0.34	10.15	10.02	-1.30	

Date ICP Performed	ICP #	Measurements of Standard Solutions						Comments
		Cd			Te			
		Nominal PPM	Measured PPM	Error %	Nominal PPM	Measured PPM	Error %	
01/14/04	21(B)	98.44	94.55	-3.95	100.13	98.66	-1.47	Cd and Te of #27 only
		19.26	18.97	-1.51	19.45	18.96	-2.52	
		39.74	40.17	1.08	40.62	39.74	-2.16	
		98.44	93.46	-5.06	100.13	99.18	-0.95	
01/20/04	22	9.83	9.83	0.01	9.96	9.91	-0.52	Cd, Te and Cu of #28 through #32
		49.88	50.32	0.88	50.71	50.58	-0.26	
		99.13	97.72	-1.42	100.90	101.80	0.89	
		99.13	100.60	1.48	100.90	104.80	3.87	
01/30/04	23	100.90	100.80	-0.10	101.10	99.91	-1.18	Cd and Te of #33 through #38
		39.61	39.76	0.38	40.42	39.42	-2.47	
		100.90	101.00	0.10	101.10	103.50	2.37	
		39.61	39.93	0.81	40.42	40.76	0.84	

Appendix C: Lists of ICP analysis

Test #11	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	4.0 M HCL,4mL H2O2		4.0 M HCL,4mL H2O2			
	PPM	PPM	PPM	PPM	%	%
	Te	Cd	Te	Cd	Te	Cd
0	0.00	0.00	0.00	0.00	0.000	0.000
30	798.55	829.87	798.55	829.87	0.043	0.045
60	892.09	843.13	891.33	843.02	0.048	0.045
90	988.61	885.34	986.28	884.54	0.053	0.047
120	1007.89	903.49	1005.08	902.25	0.054	0.048
180	1037.71	926.66	1033.93	924.67	0.056	0.050
240	1058.85	934.24	1054.22	931.94	0.057	0.050
before 24-hour	1389.74	1113.65	1368.94	1102.58	0.074	0.059
1440	1213.45	1031.56	1202.69	1025.17	0.065	0.055
2880	1146.13	1045.66	1139.76	1038.35	0.061	0.056
Test #12	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	2.0 M HCL,4mL H2O2		2.0 M HCL,4mL H2O2			
	PPM	PPM	PPM	PPM	%	%
	Te	Cd	Te	Cd	Te	Cd
0	0.00	0.00	0.00	0.00	0.000	0.000
30	956.58	879.65	956.58	879.65	0.052	0.047
60	983.31	905.94	983.13	905.76	0.053	0.049
90	1001.52	918.17	1001.08	917.82	0.054	0.050
120	1005.84	912.51	1005.32	912.28	0.054	0.049
180	1012.64	918.23	1011.93	917.85	0.055	0.050
240	1043.23	903.29	1041.48	903.41	0.056	0.049
before 24-hour	1326.74	1116.34	1313.35	1107.72	0.071	0.060
1440	1194.26	1031.56	1187.21	1026.99	0.064	0.055
2880	1121.62	981.46	1118.55	979.64	0.060	0.053
Test #13	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	1.0 M HCL,4mL H2O2		1.0 M HCL,4mL H2O2			
	PPM	PPM	PPM	PPM	%	%
	Te	Cd	Te	Cd	Te	Cd
0	0.00	0.00	0.00	0.00	0.000	0.000
30	967.04	905.64	967.04	905.64	0.049	0.046
60	976.97	917.44	976.89	917.35	0.049	0.046
90	979.80	927.82	979.68	927.58	0.050	0.047
120	990.96	917.51	990.59	917.50	0.050	0.046
180	999.33	930.43	998.71	930.03	0.051	0.047
240	1007.35	927.11	1006.43	926.83	0.051	0.047
before 24-hour	1391.86	1137.48	1373.61	1127.72	0.069	0.057
1440	1203.13	1043.03	1194.80	1038.24	0.060	0.053
2880	1148.62	1065.10	1143.57	1058.99	0.058	0.054

Test #14	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	4.0M H2SO4,4mL H2O2		4.0M H2SO4,4mL H2O2			
	PPM	PPM	PPM	PPM	%	%
	Te	Cd	Te	Cd	Te	Cd
0	0.00	0.00	0	0	0.000	0.000
30	856.285546	783.6695633	856.29	783.67	0.053	0.049
60	934.537692	804.5170023	933.91	804.35	0.058	0.050
90	946.75	829.2757143	945.93	828.71	0.059	0.052
120	942.084181	828.3921603	941.37	827.85	0.059	0.052
180	964.786098	809.4885366	963.35	809.55	0.060	0.050
240	973.255512	811.9606299	971.48	811.92	0.061	0.051
before 24-hour	1130.49622	949.109352	1121.16	942.48	0.070	0.059
1440	1057.85888	909.586876	1052.60	905.18	0.066	0.056
2880	1045.61663	916.5166532	1041.14	911.66	0.065	0.057
Test #15	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	2.0M H2SO4,4mL H2O2		2.0M H2SO4,4mL H2O2			
	PPM	PPM	PPM	PPM	%	%
	Te	Cd	Te	Cd	Te	Cd
0	0.00	0.00	0.00	0.00	0.000	0.000
30	829.14	779.46	829.14	779.46	0.049	0.046
60	841.04	798.75	840.96	798.63	0.050	0.047
90	894.61	806.53	893.85	806.31	0.053	0.048
120	876.05	798.19	875.65	798.13	0.052	0.047
180	899.99	809.83	898.98	809.47	0.053	0.048
240	891.59	820.39	890.84	819.69	0.053	0.048
before 24-hour	1134.49	963.66	1124.45	957.48	0.066	0.056
1440	1047.12	908.42	1040.98	904.71	0.061	0.053
2880	1009.55	872.76	1005.33	870.87	0.059	0.051
Test #16	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	1.0M H2SO4,4mL H2O2		1.0M H2SO4,4mL H2O2			
	PPM	PPM	PPM	PPM	%	%
	Te	Cd	Te	Cd	Te	Cd
0	0.00	0.00	0.00	0.00	0.000	0.000
30	961.37	931.79	961.37	931.79	0.053	0.051
60	1009.61	951.95	1009.30	951.82	0.056	0.052
90	1012.61	960.24	1012.26	960.00	0.056	0.053
120	1025.75	938.68	1025.14	938.87	0.057	0.052
180	1020.07	945.19	1019.61	945.20	0.056	0.052
240	1030.51	938.94	1029.71	939.15	0.057	0.052
before 24-hour	1338.69	1153.62	1325.84	1145.45	0.073	0.063
1440	1206.03	1064.76	1199.23	1060.63	0.066	0.058
2880	1124.18	1040.84	1121.64	1037.96	0.062	0.057

Test #17	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	1.0 M HCL, 1.5mL H2O2		1.0 M HCL, 1.5mL H2O2			
	PPM	PPM	PPM	PPM	%	%
	Te	Cd	Te	Cd	Te	Cd
0	0.00	0.00	0.00	0.00	0.000	0.000
30	692.96	821.07	692.96	821.07	0.037	0.044
60	905.34	951.13	903.88	950.24	0.048	0.050
90	879.37	938.19	878.27	936.80	0.047	0.050
120	903.46	926.82	901.86	925.51	0.048	0.049
150	898.37	925.22	896.92	923.96	0.048	0.049
180	898.00	914.23	896.56	913.33	0.048	0.049
240	946.72	923.76	943.27	922.48	0.050	0.049
1440	1277.91	982.87	1258.57	978.75	0.067	0.052
Test #18	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	1.0 M HCL, 2.5mL H2O2		1.0 M HCL, 2.5mL H2O2			
	PPM	PPM	PPM	PPM	%	%
	Te	Cd	Te	Cd	Te	Cd
0	0.00	0.00	0.00	0.00	0.000	0.000
30	807.57	884.03	807.57	884.03	0.043	0.047
60	909.63	924.27	908.93	923.99	0.048	0.049
90	921.32	909.72	920.45	908.71	0.049	0.048
120	960.60	958.29	958.93	957.01	0.051	0.051
150	978.52	907.95	976.35	908.05	0.052	0.048
180	981.82	971.93	979.54	969.83	0.052	0.052
240	1016.18	936.21	1012.48	935.58	0.054	0.050
1440	1283.05	1005.26	1266.48	1001.31	0.067	0.053
Test #19	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	1.0M H2SO4, 1.5mL H2O2		1.0M H2SO4, 1.5mL H2O2			
	PPM	PPM	PPM	PPM	%	%
	Te	Cd	Te	Cd	Te	Cd
0	0.00	0.00	0.00	0.00	0.000	0.000
30	886.63	972.48	886.63	972.48	0.049	0.054
60	1011.07	1006.13	1010.08	1005.86	0.056	0.055
90	1038.03	1036.16	1036.60	1035.41	0.057	0.057
120	1060.69	1015.90	1058.72	1015.63	0.058	0.056
150	1077.09	1062.21	1074.59	1060.46	0.059	0.058
180	1084.83	1061.81	1082.03	1060.08	0.060	0.058
240	1106.22	1049.56	1102.39	1048.42	0.061	0.058
1440	1382.63	1071.45	1363.33	1069.09	0.075	0.059
Test #20	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	1.0M H2SO4, 2.5mL H2O2		1.0M H2SO4, 2.5mL H2O2			
	PPM	PPM	PPM	PPM	%	%
	Te	Cd	Te	Cd	Te	Cd
0	0.00	0.00	0.00	0.00	0.000	0.000
30	820.17	824.88	820.17	824.88	0.047	0.047
60	970.80	920.79	969.81	920.17	0.055	0.052
90	1028.73	960.46	1026.98	959.31	0.058	0.055
120	1056.47	973.80	1054.18	972.39	0.060	0.055
150	1064.45	965.70	1061.95	964.51	0.060	0.055
180	1076.39	978.71	1073.50	977.09	0.061	0.056
240	1105.02	942.27	1101.01	942.08	0.063	0.054
1440	1312.19	989.50	1298.67	987.14	0.074	0.056

Test #23	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	1.0M H2SO4 first-used,4mL H2O2		1.0M H2SO4 first-used,4mL H2O2			
	PPM Te	PPM Cd	PPM Te	PPM Cd	% Te	% Cd
0	0.00	0.00	0.00	0.00	0.000	0.000
30	1904.40	1753.93	1904.40	1753.93	0.051	0.048
60	1910.88	1754.39	1910.84	1754.39	0.051	0.048
120	1959.95	1760.67	1959.33	1760.59	0.054	0.048
180	2063.97	1832.15	2061.51	1830.80	0.060	0.052
240	2109.64	1893.89	2106.09	1891.08	0.063	0.056
300	1963.95	1769.37	1964.72	1770.25	0.054	0.049
1080	2113.31	1870.56	2108.77	1867.85	0.063	0.055
1440	2092.77	1896.75	2089.08	1892.95	0.062	0.056
starting agent d	1080.31	979.54	1080.31	979.54		
Test #24	Concentration of leaching solution				Percentage in glass	
	Original data		Normalized data			
Leaching Time Minute	1.0M H2SO4 first-used,2mL H2O2		1.0M H2SO4 first-used,2mL H2O2			
	PPM Te	PPM Cd	PPM Te	PPM Cd	% Te	% Cd
0	0.00	0.00	0.00	0.00	0.000	0.000
30	1953.20	1816.94	1953.20	1816.94	0.053	0.051
60	1932.26	1812.98	1932.38	1813.00	0.052	0.051
120	1998.21	1814.32	1997.59	1814.33	0.056	0.051
180	1977.34	1747.83	1977.07	1748.96	0.055	0.047
240	2008.16	1799.92	2007.19	1799.88	0.056	0.050
300	2049.44	1811.83	2047.31	1811.45	0.059	0.051
1080	2120.09	1829.41	2115.57	1828.44	0.063	0.052
1440	2009.95	1804.55	2009.78	1804.56	0.057	0.050
starting agent d	1080.31	979.54	1080.31	979.54		

Test #25	Concentration of leaching solution						Percentage in glass		
	Original data			Normalized data					
Leaching Time Minute	2.0M H2SO4,17mL H2O2			2.0M H2SO4,17mL H2O2					
	PPM Te	PPM Cd	PPM Cu	PPM Te	PPM Cd	PPM Cu	% Te	% Cd	% Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
30	735.32	706.67	18.11	735.32	706.67	18.11	0.039	0.038	0.001
60	727.91	721.17	33.42	727.93	721.12	33.38	0.039	0.039	0.002
120	744.75	709.38	77.24	744.67	709.41	76.92	0.040	0.038	0.004
180	753.91	714.69	136.12	753.74	714.66	135.24	0.040	0.038	0.007
240	770.80	714.88	204.94	770.42	714.86	203.20	0.041	0.038	0.011
300	775.49	727.82	287.19	775.03	727.59	284.16	0.041	0.039	0.015
480	817.22	714.76	512.04	815.98	714.78	504.78	0.044	0.038	0.027
1440	883.63	727.50	967.30	880.93	727.24	950.04	0.047	0.039	0.051
2880	818.78	712.85	1102.44	817.71	712.96	1081.79	0.044	0.038	0.058
Test #26	Concentration of leaching solution						Percentage in glass		
	Original data			Normalized data					
Leaching Time Minute	1.0M H2SO4,17mL H2O2			1.0M H2SO4,17mL H2O2					
	PPM Te	PPM Cd	PPM Cu	PPM Te	PPM Cd	PPM Cu	% Te	% Cd	% Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
30	729.35	738.25	13.39	729.35	738.25	13.39	0.037	0.038	0.001
60	758.13	773.61	26.52	757.98	773.43	26.45	0.039	0.039	0.001
120	770.12	776.66	60.81	769.84	776.44	60.38	0.039	0.040	0.003
180	792.14	796.68	99.47	791.52	796.15	98.42	0.040	0.041	0.005
240	799.55	773.64	142.05	798.77	773.59	140.11	0.041	0.039	0.007
300	814.37	790.71	190.99	813.20	790.21	187.76	0.041	0.040	0.010
480	859.94	787.69	321.72	857.32	787.28	314.36	0.044	0.040	0.016
1440	932.85	799.55	574.20	927.54	798.71	557.52	0.047	0.041	0.028
2880	878.52	783.70	773.89	875.51	783.53	748.80	0.045	0.040	0.038
Test #27	Concentration of leaching solution					Percentage in glass			
	Original data		Normalized data						
Leaching Time Minute	1.0M H2SO4 second-used,2.0mL H2O2		1.0M H2SO4 second-used,2.0mL H2O2						
	PPM Te	PPM Cd	PPM Te	PPM Cd	% Te	% Cd			
0	0.00	0.00	0.00	0.00	0.000	0.000			
30	2598.00	2263.59	2598.00	2263.59	0.049	0.041			
60	2582.60	2371.43	2582.73	2370.52	0.048	0.050			
120	2607.17	2292.65	2606.88	2293.07	0.050	0.044			
180	2571.87	2362.81	2572.48	2361.45	0.047	0.049			
240	2577.71	2261.43	2578.12	2263.50	0.047	0.041			
420	2545.21	2211.11	2547.00	2215.31	0.045	0.037			
1440	2537.47	2219.02	2539.65	2222.82	0.044	0.038			
2880	2680.72	2325.44	2674.41	2322.94	0.055	0.046			
starting agent c	1998.84	1759.63	1998.84	1759.63					

Test #28	Original data			#28 Normalized Results			Percentage in glass		
Leaching	3.2M H2SO4,3.78mL H2O2			3.2M H2SO4,3.78mL H2O2					
Time	PPM	PPM	PPM	PPM	PPM	PPM	%	%	%
Minute	Te	Cd	Cu	Te	Cd	Cu	Te	Cd	Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
300	1495.56	1343.76	730.62	1495.56	1343.76	730.62	0.041	0.037	0.020
600	1500.62	1323.08	1388.20	1500.49	1323.61	1371.32	0.041	0.036	0.038
1440	1509.20	1320.88	1711.38	1508.63	1321.52	1677.90	0.041	0.036	0.046
Test #29	Original data			#29 Normalized Results			Percentage in glass		
Leaching	2.0M H2SO4,3.613mL H2O2			2.0M H2SO4,3.613mL H2O2					
Time	PPM	PPM	PPM	PPM	PPM	PPM	%	%	%
Minute	Te	Cd	Cu	Te	Cd	Cu	Te	Cd	Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
300	1605.28	1497.72	263.09	1605.28	1497.72	263.09	0.041	0.039	0.007
600	1620.88	1496.54	306.83	1620.48	1496.57	305.71	0.042	0.039	0.008
1440	1619.22	1472.90	364.98	1618.91	1474.13	360.91	0.042	0.038	0.009
Test #30	Original data			#30 Normalized Results			Percentage in glass		
Leaching	2.0M H2SO4,1.8mL H2O2			2.0M H2SO4,1.8mL H2O2					
Time	PPM	PPM	PPM	PPM	PPM	PPM	%	%	%
Minute	Te	Cd	Cu	Te	Cd	Cu	Te	Cd	Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
300	1705.03	1631.52	109.30	1705.03	1631.52	109.30	0.042	0.041	0.003
600	1736.00	1641.68	128.38	1735.18	1641.41	127.88	0.043	0.041	0.003
1440	1773.58	1623.24	136.27	1770.78	1623.95	135.36	0.044	0.040	0.003
Test #31	Original data			#31 Normalized Results			Percentage in glass		
Leaching	1.0M H2SO4,3.613mL H2O2			1.0M H2SO4,3.613mL H2O2					
Time	PPM	PPM	PPM	PPM	PPM	PPM	%	%	%
Minute	Te	Cd	Cu	Te	Cd	Cu	Te	Cd	Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
300	1572.40	1566.20	1278.77	1572.40	1566.20	1278.77	0.038	0.038	0.031
600	1531.45	1586.80	1481.06	1532.52	1586.26	1475.78	0.037	0.039	0.036
1440	1544.11	1598.96	1571.66	1544.52	1597.79	1561.65	0.038	0.039	0.038
Test #32	Original data			#32 Normalized Results			Percentage in glass		
Leaching	1.0M H2SO4,1.80mL H2O2			1.0M H2SO4,1.80mL H2O2					
Time	PPM	PPM	PPM	PPM	PPM	PPM	%	%	%
Minute	Te	Cd	Cu	Te	Cd	Cu	Te	Cd	Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
300	1513.69	1517.92	422.08	1513.69	1517.92	422.08	0.036	0.036	0.010
600	1558.66	1504.75	651.88	1557.50	1505.09	645.95	0.037	0.036	0.015
1440	1572.32	1499.78	774.61	1570.45	1500.38	762.33	0.038	0.036	0.018

Test #33	Original data			#33 Normalized Results			Percentage in glass		
Leaching	3.2M H2SO4,3.78mL H2O2			3.2M H2SO4,3.78mL H2O2					
Time	PPM	PPM	PPM	PPM	PPM	PPM	%	%	%
Minute	Te	Cd	Cu	Te	Cd	Cu	Te	Cd	Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
60	1598.15	1427.25	42.94	1598.15	1427.25	42.94	0.043	0.038	0.001
120	1625.06	1419.31	61.84	1623.99	1419.62	61.09	0.043	0.038	0.002
300	1665.19	1424.38	82.04	1660.95	1424.29	79.69	0.044	0.038	0.002
Test #34	Original data			#34 Normalized Results			Percentage in glass		
Leaching	2.0M H2SO4,3.613mL H2O2			2.0M H2SO4,3.613mL H2O2					
Time	PPM	PPM	PPM	PPM	PPM	PPM	%	%	%
Minute	Te	Cd	Cu	Te	Cd	Cu	Te	Cd	Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
60	1456.06	1388.29	127.93	1456.06	1388.29	127.93	0.038	0.036	0.003
120	1490.65	1403.22	287.66	1489.69	1402.80	283.21	0.039	0.036	0.007
300	1521.93	1387.11	897.33	1519.23	1387.59	858.92	0.039	0.036	0.022
Test #35	Original data			#35 Normalized Results			Percentage in glass		
Leaching	2.0M H2SO4,1.8mL H2O2			2.0M H2SO4,1.8mL H2O2					
Time	PPM	PPM	PPM	PPM	PPM	PPM	%	%	%
Minute	Te	Cd	Cu	Te	Cd	Cu	Te	Cd	Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
60	1698.46	1634.01	86.20	1698.46	1634.01	86.20	0.043	0.041	0.002
120	1738.74	1655.34	121.18	1737.39	1654.62	120.01	0.044	0.042	0.003
300	1842.76	1689.93	268.23	1834.45	1686.90	257.21	0.046	0.043	0.007
Test #36	Original data			#36 Normalized Results			Percentage in glass		
Leaching	1.0M H2SO4,3.613mL H2O2			1.0M H2SO4,3.613mL H2O2					
Time	PPM	PPM	PPM	PPM	PPM	PPM	%	%	%
Minute	Te	Cd	Cu	Te	Cd	Cu	Te	Cd	Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
60	1779.96	1698.10	90.74	1779.96	1698.10	90.74	0.044	0.042	0.002
120	1841.91	1714.27	171.48	1839.80	1713.72	168.72	0.045	0.042	0.004
300	1899.14	1717.76	289.36	1893.12	1716.97	278.56	0.046	0.042	0.007
Test #37	Original data			#37 Normalized Results			Percentage in glass		
Leaching	1.0M H2SO4,1.80mL H2O2			1.0M H2SO4,1.80mL H2O2					
Time	PPM	PPM	PPM	PPM	PPM	PPM	%	%	%
Minute	Te	Cd	Cu	Te	Cd	Cu	Te	Cd	Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
60	1779.21	1716.01	100.64	1779.21	1716.01	100.64	0.043	0.041	0.002
120	1871.27	1772.74	255.52	1868.70	1771.16	251.20	0.045	0.043	0.006
300	1914.06	1696.61	512.54	1909.11	1699.27	493.88	0.046	0.041	0.012
Test #38	Original data			#38 Normalized Results			Percentage in glass		
Leaching	1.0M H2SO4,3.613mL H2O2			1.0M H2SO4,3.613mL H2O2					
Time	PPM	PPM	PPM	PPM	PPM	PPM	%	%	%
Minute	Te	Cd	Cu	Te	Cd	Cu	Te	Cd	Cu
0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
60	821.56	800.41	62.45	821.56	800.41	62.45	0.042	0.040	0.003
120	851.17	807.13	139.80	850.78	807.04	138.80	0.043	0.041	0.007
300	913.86	839.22	389.63	911.85	838.30	382.14	0.046	0.042	0.019